COMPOSITE CASTING
SUPERIOR STRUCTURAL MATERIALS THROUGH THE COMBINED APPLICATION OF UNIQUE ZERO-G EFFECTS

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ABSTRACT

Composite casting is of particular interest for the demonstration of space manufacturing capabilities in early experiments, since it (1) permits the application of basic zero-g processing concepts in a variety of effective combinations, and (2) has a high assurance of experiment success. In conceptual terms, composite casting has been adequately defined in previous presentations and papers. The purpose of this discussion is to assess the effectiveness of various modifications and to propose specific experiments.

The basic process, which employs primarily the zero-g phenomenon of mixture stability, comprises two methods: mold casting and free casting. The attainable end-product properties are determined by proper selection of matrix and reinforcement materials and by optimization of reinforcement shape, size and packing. Further improvement of properties may be achieved by the individual or combined application of the following modifications:

1. Modifications for strength optimization: Variable reinforcement distribution; and controlled reinforcement orientation.

2. Modifications for the improvement of ductility: grain refinement by the use of closely packed microsize reinforcements, acting as nucleation sites; and further matrix microstructure control by finely dispersed micro-particles.

Potential techniques and expected capabilities for each modification and various combinations are discussed in detail. Fundamental and technological problems for mold and free casting are identified, together with potential ways of solution in either laboratory investigations or in the context of other space experiments.

An experiment program is proposed, specifying individual experiment conditions (materials, batch size, mold shape), equipment requirements (design, vehicle arrangement, support requirements), operations (controls, astronaut assistance) and expected results. The proposed experiment schedule, providing for a gradual increase of capabilities and an effective correlation with other experiments, is based on presently planned vehicle availability (workshop, space station) and on anticipated experiment hardware leadtimes.

INTRODUCTION: BACKGROUND

The concept of composite casting as a unique space manufacturing process has been introduced in earlier reports (Ref. 1, 2, 3). Its ultimate objective is the production of high-performance structural materials and components directly from the melt, circumventing the long and expensive sequence of processing steps necessary for non-reinforced metals, such as ingot production, rolling, forging, and machining.

The potential of composite materials is undisputed; numerous types of polymer-matrix composites such as "fiberglass" have become common construction materials, in aerospace engineering as well as in consumer goods. At the same time, whiskers whose mechanical properties exceed the presently used polycrystalline or amorphous fibers by at least one order of magnitude, have never been successfully integrated into metal-base composites, simply because they do not lend themselves to the mating with the matrix in the solid state dictated by gravity in terrestrial production.

This confinement led to the use of single crystals in the form of comparatively thick filaments, such as boron filaments. Even though highly attractive for specific applications, such filamentary composites have inherent limitations:

1. The preferred orientation of reinforcement and, consequently, properties limits the application to specific shapes, and presents serious joining assembly problems.
2. In polymer-base filamentary composites, the low shear strength of the matrix prohibits full exploitation of the filament strength.
3. In metal-base filamentary composites, the high shear strength and stress-redistribution capability of the matrix is fully effective only at lower packing densities; the desirable high packing densities are impaired by the difficulty of achieving reliable diffusion bonds in the matrix and by extensive filament damage resulting from the high diffusion bonding pressures.

An ideal material, therefore, would be a metal whisker composite with a continuous matrix and isotropic property distribution. Manufacturing such a material in the solid state by diffusion bonding is unfeasible: manufacturing it in the liquid-matrix state is precluded under terrestrial conditions by the gravity-induced whisker segregation. The phenomenon of absolute mixture stability characteristic to zero-g, therefore, offers the unique opportunity to produce homogenous metal-whisker composites by means of casting; it further permits fabricating complex components from these materials in a single operation. As will be shown later, further material improvements may be attainable by various combinations of zero-g processing techniques.

DEFINITION OF "COMPOSITE CASTING"

The term "composite casting" is used here in a broad sense and comprises the following methods and materials:

Casting methods:

1. Mold-casting.
2. Free casting of ingots, primarily in the form of spheres.
3. Free-formed shapes with the use of induced forces.
4. Adhesion casting.

Materials

1. Matrices reinforced with whiskers, fibers, flakes, ribbons, etc.
2. Matrices with dispersed particles.
3. Combinations of (1) and (2).

ATTRACTIVENESS FOR SPACE EXPERIMENTS

Composite casting has been selected for this discussion for six reasons:

1. It is unique to the zero-g or a low-g environment.
2. While already attractive in its basic form, it offers a variety of combinations of typical zero-g phenomena. It therefore, permits the demonstration of a variety of zero-g effects.
3. The basic concept is straightforward and its tooling requirements comparatively simple; thus it offers a high assurance of success.
4. It involves a number of typical zero-g methods and tooling problems and may serve, thereby, as a general testbed for zero-g manufacturing engineering.
5. Extensive use can be made of the advanced state of the art in conventional composites, resulting from their intensified promotion during the last decade (Ref. 4 to 11).
6. The products have immediate applications (customers) and will result in a substantial advancement in high-performance structures.

PROCESS CONCEPTS

The basic process of composite casting has the objective to produce high-strength materials and components consisting of a metal matrix and random-oriented reinforcements of various materials, forms, and packing densities. Preferred reinforcement orientation or variable distribution may be achieved by means of induced forces. By proper material selection, the reinforcements may further act as nucleation sites, producing grain refinement associated with improved ductility. Grain refinement may be increased by orders of magnitude by the dispersion of micro-particles of appropriate materials throughout the matrix; this may be used in the conjunction with fiber reinforcements for high strength and ductility, or without reinforcements with the potential of producing polycrystalline components of essentially mill-product quality directly from the melt (Ref. 1).

The basic process may be further modified by generating gas bubbles in the interfiber matrix, producing a high-stiffness, low-density material. Consequently, composite casting comprises the following processes and products:

1. Casting metal matrix-random fiber composites with isotropic high strength and stiffness.
2. Casting metal matrix composites with controlled fiber orientation or distribution.
3. Casting fine-grain polycrystalline materials by means of finely dispersed micro-particles.
4. Casting fiber-reinforced composites with high ductility by combination of (1) and (3).
5. Casting high stiffness-low density materials by introducing a partially foamed matrix in (1) or (4).

Table 1 identifies the five versions of composite casting in terms of the employed zero-g effects, together with several other space manufacturing concepts for comparison. The prime effect, common to all process modifications, is that of mixture stability.

Table 1. Zero-g effects employed in selected processes.

PROCESS/PRODUCT		NO CONTAINER	INTERMOLEC. FORCES		NO MASS ACCEL.		INDUCED FORCES	
			INTRINSIC	CONTACT/ CAPILLARITY	MIXTURE STABILITY	ZERO CONVECT.	FORM CONTROL	POSITION CONTROL
COMPOSITE CASTING	MOLD			Ⓣ	●	O		
	FREE	●		Ⓣ	●	O	O	Ⓣ
	DISPERSION			Ⓣ	●	O		
	ORIENTATION			Ⓣ	●	O		
	LOW DENSITY		●	Ⓣ	●	O		
ADHESION CASTING			●	●				
LIQUID FORMING		●	●	Ⓣ			●	Ⓣ
BLOW FORMING		O	●	Ⓣ			O	
FOAMS		O	●	Ⓣ			O	
GLASSES		●	O			O	O	Ⓣ
SINGLE CRYSTALS	FROM GAS					●	O	
	FROM MELT	●				●	O	Ⓣ
SUPERCOOLING		O				O		
SUPERSATURATION					●	O		
METAL COMPOUNDS					●	O	O	

● PRIMARY FUNCTIONAL
O SECONDARY FUNCTIONAL
Ⓣ TOOLING REQUIREMENT

MATERIALS AND COMPOSITE SELECTION

In view of the absence of terrestrial limitations to composite fabrication, composite casting offers a wide spectrum of potential matrix and reinforcement combinations. The applicable data for several matrix and reinforcement materials are listed in Tables 2 and 3.

Table 2. Applicable properties of selected matrix materials (in order of increasing melting temperatures).

PROPERTIES/MATERIAL	Sn	Mg	Al	Ag	Cu	Ni	Fe	Ti
MELTING TEMP (°F)	450	1202	1220	1761	1981	2650	2800	3300
DENSITY (GM/CM^3)	7.30	1.74	2.36	9.26	8.96	8.90	7.87	4.54
HEAT R.T. TO FUSION (BTU/LB)	241.2	300.5	254.1	95.7	180.5	265.1	308.2	362.3
HEAT OF FUSION (BTU/LB)	25.6	154.2	166.7	45.6	88.1	133.6	115.4	169.1
SPECIFIC HEAT/LIQUID (BTU/LB/°F)	0.06	0.33	0.26	0.07	0.12	0.15	0.15	0.12
VISCOSITY/LIQUID (DYNE-SEC./CM^2)	0.017	0.011	0.029	0.039	0.034	0.05	0.040	
SURFACE TENSION/LIQUID (DYNE/CM)	550	542	900	1140	1280	1930	1500	1510

Table 3. Properties of potential reinforcements.

MATERIAL	MELTING TEMP. (°F)	DENSITY (G/CM^3)	DIAMETER (MICRONS)	LENGTH (MICRONS)	STRENGTH (10^6 PSI)	ELASTIC MODULUS (10^6 PSI)	COST ($/LB.)
WHISKERS							
Al_2O_3-α (SAPPHIRE)	3780	3.97	1-30	50-2000	0.5-3.5	60-150	9000
Al_2O_3-α/Al N	4000	3.6	3-30	30-600	0.5-2.0	50-100	900
SiC	4200	3.21	1-10	20-400	2-6	80-150	3000-11,000
SiC/Al_2O_3-α	4000	3.6	2-30	20-1000	2-6	60-150	900
Si_3N_4	3450	3.1	1-10		0.7-2	55	
BeO	4650	2.78			1.8	50	
GRAPHITE	6700	2.22	0.5	1 CM	2.8	~100	MILLIONS
OTHERS							
GRAPHITE FIBERS	6700	2.22	7	ANY	0.5	~100	350
BORON FILAMENT	4200	2.3	100	ANY	0.3-1.5	60	300
Be CHOPPED WIRE	2340	1.82	100	ANY	0.18	40	2000

For initial space experiments, selection of materials was based on the following criteria:

Matrix-whisker compatibility

Expected composite properties

Whisker availability, state-of-art

Typicality (representative of a group of materials)

Minimum secondary material problems

Minimum processing and tooling problems

Product usefulness (applications)

Material cost

The evaluation of various feasible matrix and reinforcement combinations indicated the best overall experiment effectiveness for the following material systems:

1. Aluminum matrix, reinforced with sapphire whiskers or mixed whiskers of sapphire and aluminum nitride.
2. Nickel matrix, reinforced with silicon carbide whiskers.

The two selected systems are representative of two major material groups, so that the data and processing experience gained in experiments will be useful for a wide spectrum of composite casting applications.

The aluminum system is typical of light-metal matrices aimed at high strength and stiffness to weight ratio. Processing temperatures are moderate and the cooling rates by radiation to space environment rather low. The nickel system is primarily aimed at superior high-temperature components with high creep strength and oxidation resistance. It serves as a model for a wide varity of nickel, cobalt, and ferrous alloys as matrix materials. Its high processing temperatures require a modified line of tooling. Heating requirements in terms of Btu/lb. are essentially the same for both systems; on the basis of equal volume (which may be more meaningful for casting of components), they differ by a factor of 2.5.

BASIC PROCESS

The "basic process" refers to casting random mixture of matrix and reinforcements only. Attainable mechanical properties are determined by (1) properties of component materials and (2) the reinforcement content.

The beneficial effect of low whisker contents in Al and Ni matrices has been demonstrated by work carried out by the Mitron Research & Development Corporation under the sponsorship of OART and MSFC (Ref. 12). It was shown that sapphire whiskers, coated with Ni for weldability, assume random positions across the grains, producing a mechanical interlocking effect (Figure 1a). The gains in mechanical properties obtained at whisker contents of less than 0.1% are summarized in Table 4. While these gains are moderate, they support the basic concept of strengthening with random-oriented reinforcements.

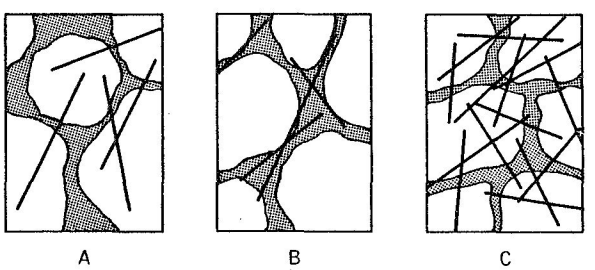

Figure 1. Effect of random-oriented whiskers on microstructure.

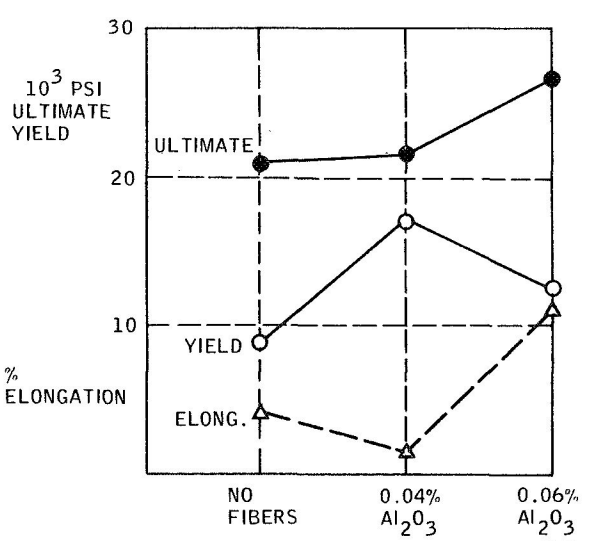

Figure 2. Effect of two whisker materials on mechanical properties of cast aluminum alloy 2024.

As illustrated in Figure 2, the mechanical properties may be controlled by reinforcement modifications. While sapphire fibers reduce the ductility (elongation), a full recovery and increased strength is obtained by addition of Al-N whiskers.

Nonwetting whiskers tend to position themselves in the grain boundaries (Figure 1b); this has no effect upon room temperature properties, yet increases creep resistance at high temperatures.

At high reinforcement contents (Figure 1c), the increase of stiffeners (elastic modulus) is adequately determined by the rule of mixtures; i.e., it is proportional to the reinforcement/matrix ratio. The strengthening effect is quite complex, yet is primarily the result of mechanical interlocking, deformation constraint and multiaxial stress distribution in the interfiber matrix.

Table 4. Effect of small fiber contents on mechanical properties of cast aluminum alloy (2024).

FIBERS			MATRIX	STRENGTH			YIELD		ELONGAT.	
MATERIAL	STRENGTH (10^6 PSI)	VOL. %	POST-CAST TREATMENT	PREDICT. X	10^3 PSI	X	10^3 PSI	X	%	X
–	–	0	AS CAST		21.0	1	8.7	1	4.0	1
Al_2O_3	1.5	0.043		1.015	21.7	1.03	17.3	2.0	1.0	0.25
Al_2O_3 + Al N	1.2	0.063		1.02	26.8	1.28	12.5	1.44	11.6	2.9
–	–	0	SOLUTION HEAT TREATED & AGED	1	33.0	1	26.1	1	3.8	1
Al_2O_3	1.5	0.043		1.01	33.9	1.03	25.5	0.98	1.0	0.26
Al_2O_3 + Al N	1.2	0.063		1.01	32.4	0.98	25.5	0.98	2.5	0.63
		0.230		34.4 1.04	43.0	1.31	29.2	1.12	2.5	0.63

FIBER DIMENSIONS: Al_2O_3:DIAM. 10-30μ LENGTH 125-2,500μ
ALN :DIAM. 3-30μ LENGTH 30-600μ
1 MIL 5-100 MIL
1 MIL 1-24 MIL

The maximum attainable reinforcement contents have been determined by tests with equal-density models. It is primarily dependent upon the length-to-diameter ratio (L/D) of the whiskers. As shown in Figure 3, the maximum density for random-oriented fibers of high L/D, which are of prime interest, is in the order of 25%. It may be increased by vibrations. However, it is expected that, in view of the complex strengthening mechanism, highest fiber contents may not even be desirable and that an optimum condition is achieved at a specific content for each system. Preliminary data on the effect of packing density are the subject of laboratory experiments presently in progress; the final answer can, however, only be obtained in space experiments.

While this implies that accurate strength predictions are impossible at this time, a tentative assessment of the strengthening effect has been made with the rule of mixtures and an estimated composite effectiveness factor. The expected mechanical properties of the two selected composite systems are presented in Figure 4 for various whisker types and contents. In Figure 5 the strength is compared with conventional monolithic materials on the basis of equal weight. Even at low whisker contents, the expected strength-to-weight ratio substantially surpasses any present, high-strength structural alloy.

The uniform mixture distribution attainable under zero-g, together with the high fluidity of molten metals, permits the movement of individual fibers with small induced forces. Both variable fiber distribution (fiber concentration) and fiber orientation as alignment are most effectively achieved by the combined

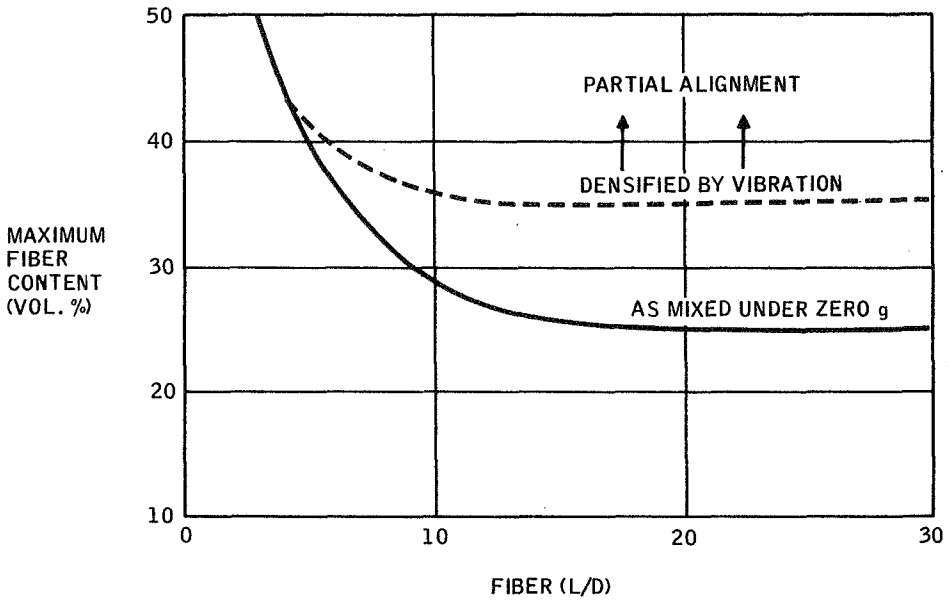

Figure 3. Highest attainable fiber contents for random orientation.

action of vibrations and a directional force. The vibrations, generated either mechanically or by an alternating electromagnetic field, have the purpose to free the fibers from their interlocked position and to ensure high mobility. The directional force is provided by either an electromagnetic or an electrostatic field. Both are applied simultaneously after casting prior to solidification. The effect of various moves can be well demonstrated and evaluated with equal-density models.

By combination of the basic process with zero-g methods of nucleation and crystallization control, products may be achieved that exhibit not only superior strength and stiffness, but also high ductility. Improved ductility may already be obtained in the basic process, as the individual whiskers will undoubtedly generate grain segmentation during solidification or act as nucleation sites. The resulting grain size will be substantially smaller than obtainable in conventional casting (Figure 6a).

A considerably higher degree of grain refinement and, consequently, ductility may be achieved by the generation of a high number of nucleation sites in the form of finely dispersed microparticles whose uniform distribution is assured by the zero-g phenomenon of mixture stability (Figure 6b). Effective particle materials for the Al-matrix are titanium carbide or titanium boride, which will

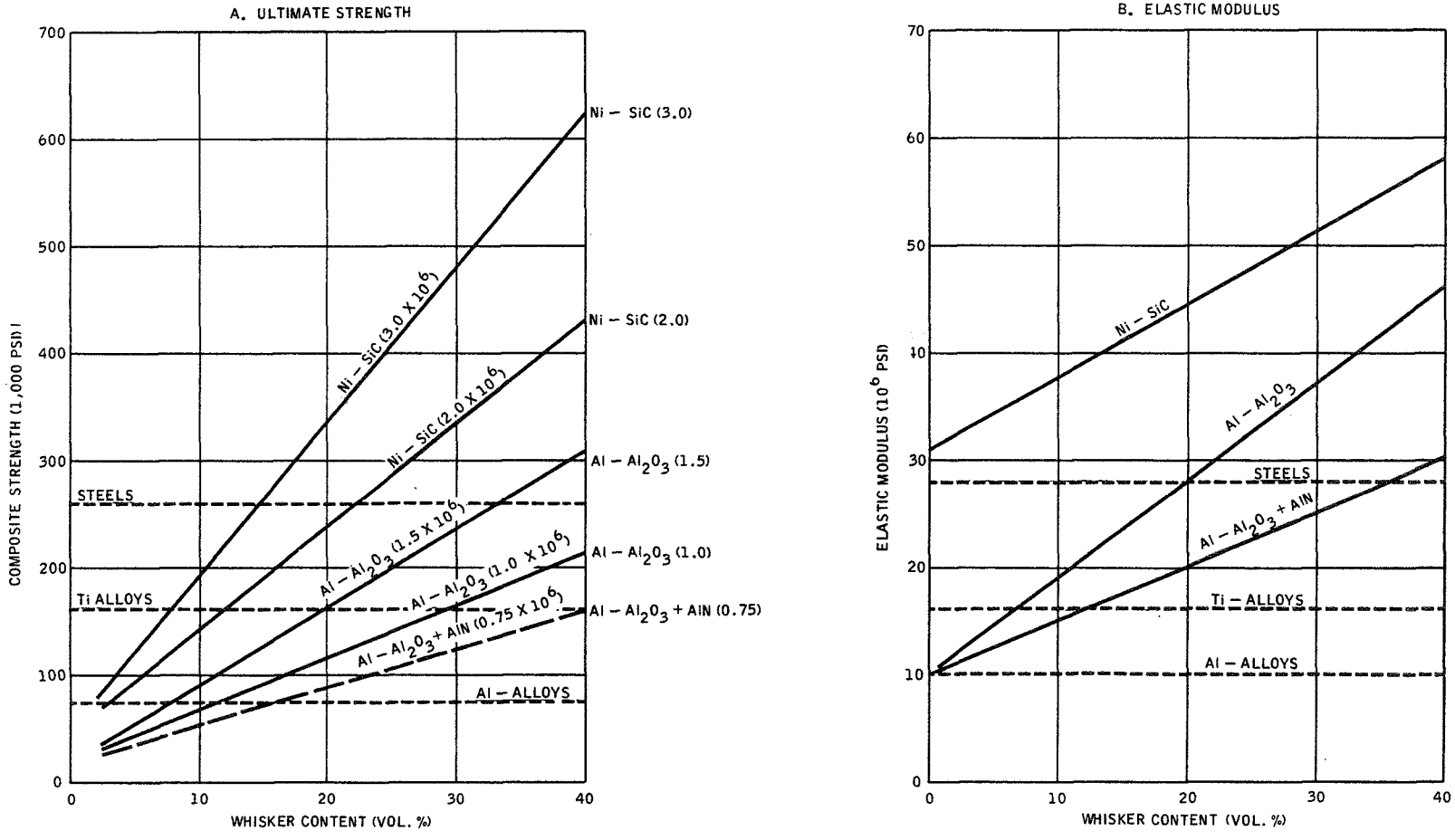
A. ULTIMATE STRENGTH
COMPOSITE STRENGTH (1,000 PSI)
WHISKER CONTENT (VOL. %)
Ni – SiC (3.0)
Ni – SiC (2.0)
Al – Al2O3 (1.5)
Al – Al2O3 (1.0)
Al – Al2O3 + AlN (0.75)
Ni – SiC (3.0 X 10^6)
Ni – SiC (2.0 X 10^6)
Al – Al2O3 (1.5 X 10^6)
Al – Al2O3 (1.0 X 10^6)
Al – Al2O3 + AlN (0.75 X 10^6)
STEELS
Ti ALLOYS
Al – ALLOYS
B. ELASTIC MODULUS
ELASTIC MODULUS (10^6 PSI)
WHISKER CONTENT (VOL. %)
Ni – SiC
Al – Al2O3
Al – Al2O3 + AlN
STEELS
Ti – ALLOYS
Al – ALLOYS

Figure 4. Expected mechanical properties of cast whisker composites in comparison with monolithic materials.

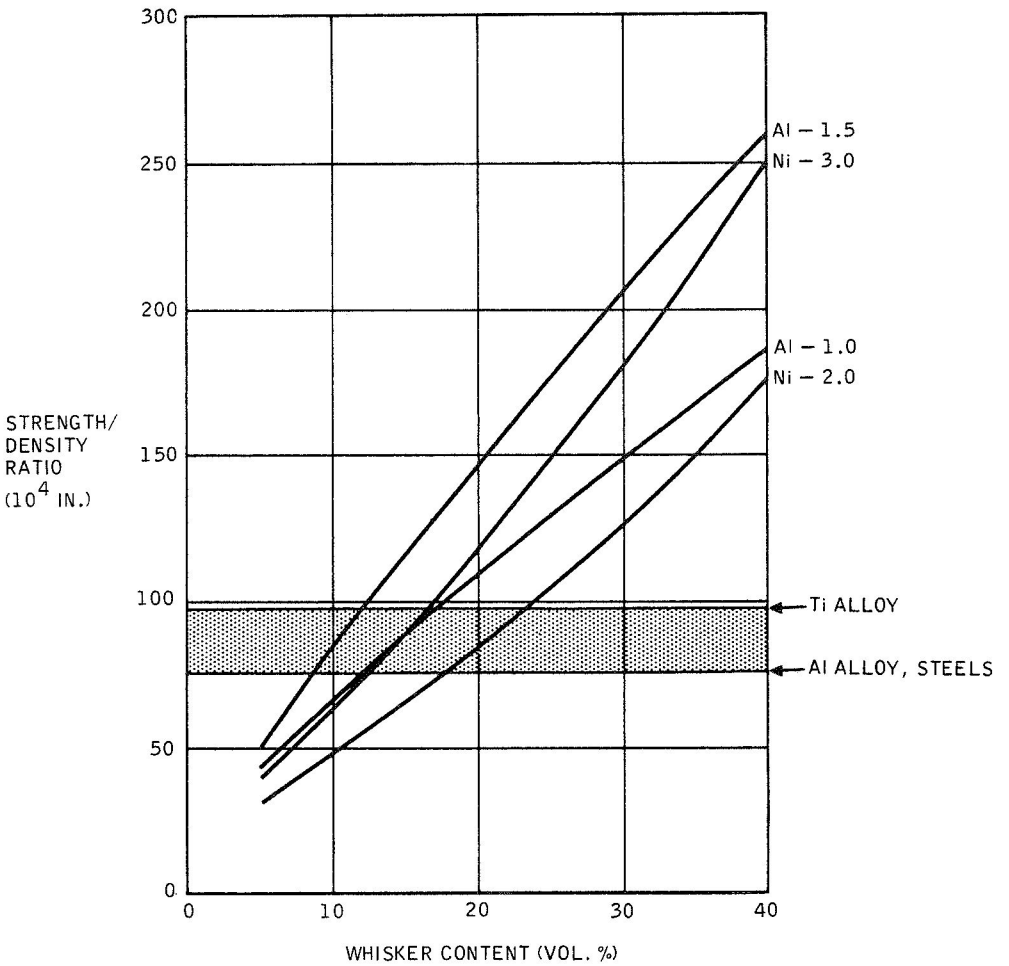

Figure 5. Strength comparison of composite castings with high-strength forgings on equal weight basis.

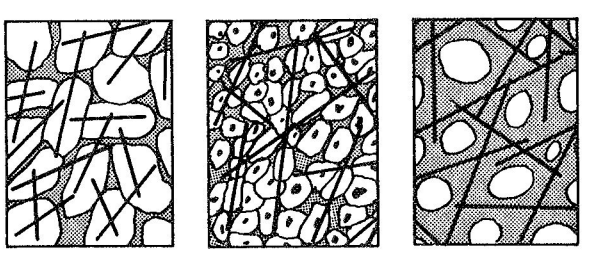

Figure 6. Microstructure of modified cast composites.

be in solution and precipitate during cooling as discrete particles a few degrees above solidification temperature. For the nickel matrix, alumina particles are expected to be effective catalysts for the achievement of a fine-grain microstructure.

These fine-grain casting techniques may be used in connection with fibers as a dual-composite, or without fibers

as a single-phase "particulate composite" with the ultimate objective of producing fine-grain polycrystalline materials and components directly from the melt.

The third modification of the basic process consists of the injection of an inert gas into the liquid matrix, to form a foamed low-density composite as illustrated in Figure 6c. The gas may be introduced during mixing or, preferably, by continuous dispersing shortly before entrance into the mold.

On the basis of equal weight, foaming will increase stiffness, while the strength remains unchanged. The low-density composite will, therefore, find application primarily in stiffness-critical structures. A foamed nickel-base composite may serve as an effective core material for lifting surface panels operating at high temperatures.

TOOLING REQUIREMENTS AND CONCEPTS

Tooling studies carried out for composite casting and a number of other zero-g processes indicate clearly that the primary problems of space manufacturing lie not in the validity of processing concepts, but rather in the required tooling — which is the key to practical application. The researcher often tends to overlook these problems mainly because they appear — at first glance — rather trival. How, for instance, can we move a liquid in the absence of gravity; or, how can we prevent formation of voids and gas bubbles in a heated liquid which on earth rise conveniently to the surface?

The solution of such problems calls for a complete disassociation from terrestrial methods, as has been pointed out repeatedly by Wuenscher (Ref. 13). It is the art of space manufacturing to take advantage of typical zero-g phenomena, rather than to attempt an awkward reproduction of the terrestrial behavior of matter.

The same necessity of departure from conventional concepts applies to equipment and operations. Methods and facilities have to be adapted to the absence of weight and preferred orientation, as well as to the space confinement and high degree of automation in orbital vehicles. This precludes the in-space development and gradual assembly of experiment equipment, starting with a "simple laboratory experiment." The low earth-orbit traffic frequency in the initial experiment period and the difficult in-space vehicle integration further precludes the successive deployment of single-purpose units with increasing complexity. Rather, for each family of experiments conventional laboratory facilities must be replaced by a single experiment machinery with a high degree of automation and remote control, fully assembled and checked out on earth and acceptable to a multitude of experiment modifications.

On the basis of these ground rules, a single experiment "apparatus" is proposed for composite casting experiments in the advanced orbital workshop. It has to combine the following major functions:

1. Containing solid and liquid material.
2. Heating and melting.
3. Transfer (moving) liquid material from the melting chamber to the mold.
4. Mixing liquid-matrix material.
5. Cooling the mold and casting solidification.
6. Environment (gas, pressure) control for open-mold casting.
7. Gas injection for foaming.
8. Contact -free generation of forces in casting material (electromagnetic, electrostatic).
9. Remote control of all functions and settings (such as temperature, pressures).
10. Minimized heat input into the vehicle.

Once conceptual design of the composite casting apparatus, which combines these functions, is shown in Figure 7. It consists of a closed system of melting chamber, melt transfer and mold, uniformly heated to the material processing temperature by radiation or induction. The mold is cooled by retracting (swing-away) the mold-heating units and radiation into deep space, supported by a small sure-pointing shadow shield. Major functional details are discussed below.

Vehicle integration and the deployment procedure are illustrated in Figure 8. Apparatus preparation, charging with material, and setting controls are carried out in position 1 inside the vehicle, with full 360-degree access. For deployment, the apparatus is moved into a vehicle-attached tube by means of telescoping rails (Position 2). After the inside hatch is sealed and the external hatch is opened, the apparatus is moved into Position 3, at least 20 feet from the vehicle, followed by the deployment of the shadow shield. Experiment performance is monitored by the astronaut via the control unit attached to the inside hatch. After cooling of the entire unit, it is retracted into the vehicle in a reversed sequence of deployment steps.

In the fully deployed Position 3 the apparatus may be removed from the guide rails by a serpentuator and carried into a favorable processing position, such as the workshop vacuum wake.

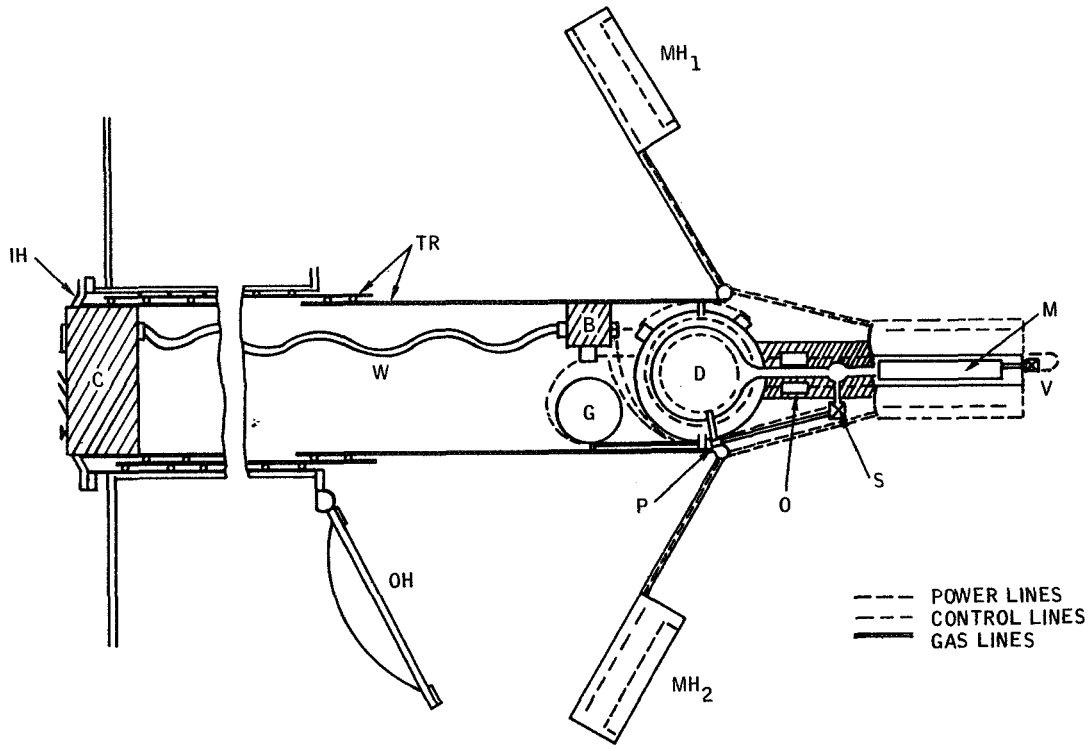

Figure 7. Composite casting apparatus in operating position.

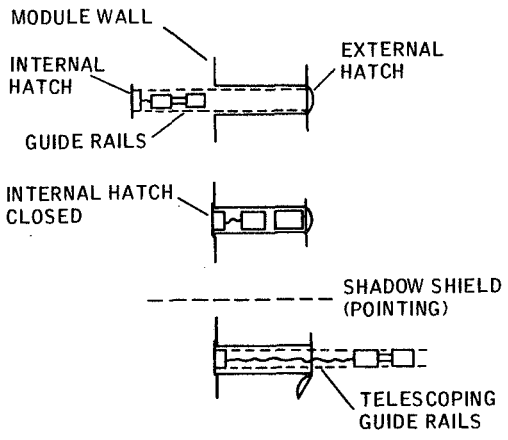

Figure 8. Experiment operations.

RAW MATERIAL FORM

Four methods of raw material supply are being considered. For large melting chambers, raw material may be provided in form of either a prepressed powder-reinforcement mixture or a precast mixture. In both cases, the reinformcement content is accurately adjusted, while the distribution across the ingot is not critical as final mixing will be accomplished upon melting in zero-g. For continuous melting, powdered metal and reinforcements are supplied either separately or premixed.

Compacted powder "ingots" will have the shape of the inner melting chamber space. For series of experiments, a number of ingots would be prepared: one for each material composition and reinforcement content. Melting chamber and ingots are dimensioned to provide sufficient material for repeated casting experiments at one composition.

For initial experimentation it may be preferable to supply for each material type a complete heating chamber-ingot assembly.

MIXING

No reliable method of liquid matrix-solid reinforcement mixing has yet been defined. Studies and experiments in progress are handicapped by the difficulty of reproducing the effect under normal gravity conditions. The problem is quite complex, as one must achieve random motion without any preferred g-force. One further has to preclude particle or fiber coagulation which, in turn, is related to interparticle forces, interfacial energies, adhesion, and matrix drag.

One feasible method is mixing in a separate centrifuge with a secondary oscillating mode; this is, however, impractical, at least for initial experiments. The most promising and simple tentative mixing technique is variable-mode vibrations of the melting chamber, induced either mechanically or with an alternating and rotating electromagnetic field.

LIQUID MANAGEMENT AND MELTING CHAMBER DESIGN

Moving liquids under zero-g requires a complete departure from conventional methods. Use of direct mechanical action — such as cylinder-piston concepts — has to be ruled out from the outset, since it is incompatible with molten metals and unnecessarily clumsy. Moving by induced g-forces, even though feasible, is similarly ruled out since it interferes with mixture integrity and represents just another attempt to reproduce terrestrial conditions in orbit.

Zero-g offers the unique capability to move liquids by interface energies with no induced forces. The suggested concepts of melt transfer are, therefore, primarily based on controlled wettability and capillary action. Supporting mechanical action is introduced only in an indirect way by the formation of pressurizing bubbles, primarily using surface tension effects.

Two melting chamber designs, employing these principles, are shown in Figures 9 and 10. In the spherical chamber, the movement of the molten material is facilitated by high wettability to all surfaces. The perforated inner sphere and its capillary effect will ensure movement of the material toward the outer sphere wall and the mold passage. Movement is supported by the pressure-controlled formation of a bubble in the center space; this bubble cannot move through the perforated inner sphere, since the small radii of any bubble-bulges at the perforation are not compatible with the bubble pressure. The second function of the bubble is absorption of vapors from the melt as they move to the liquid-gas interface.

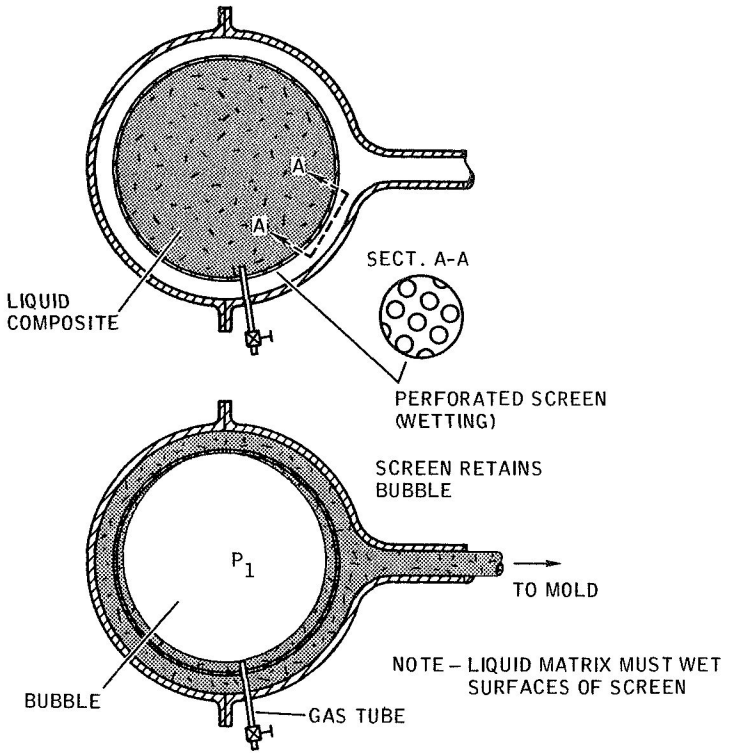

Figure 9. Spherical melting and dispensing unit.

The ellipsoidal chamber, Figure 10, employs the same principles; the function of the holes in the perforated sphere are provided by the chamber shape and the presence of two exits: the decreasing bubble radii toward the exits and the necessity of pressure balance will keep the bubble centered; movement of the bubble into the exits is impossible as long as there is any melt present. While this design has the advantage of simplicity, it is somewhat more difficult to open for charging with material.

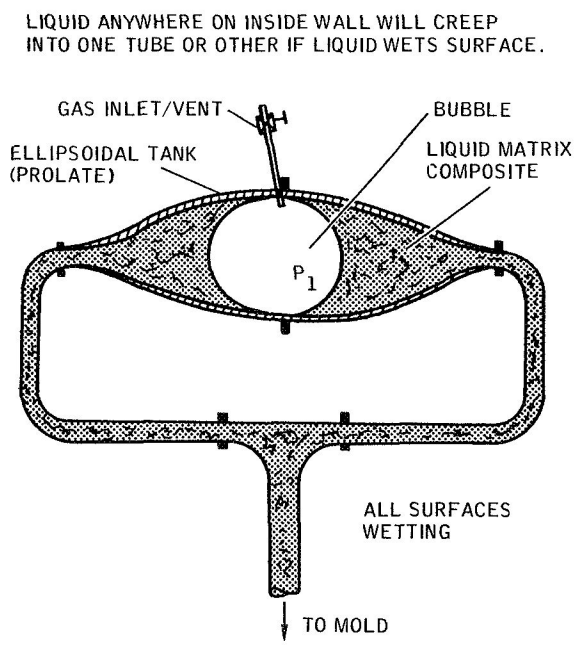

Figure 10. Ellipsoidal dispensing unit.

The design of a small melting and mixing chamber for continuous raw material supply (metal powder and reinforcements) and continuous electron-beam melting are presently under study.

For convenient removal of the casting after solidification, a clear separation from the material supply system near the mold entrance is desirable. A mechanical cutoff before solidification is impractical as it will freeze in. Instead, the generation of a gas bubble, as illustrated in Figure 11, in a bulged section of of the transfer tube ("bubble valve") not only provides an effective separation, but also is a typical application of liquid management techniques unique to zero-g.

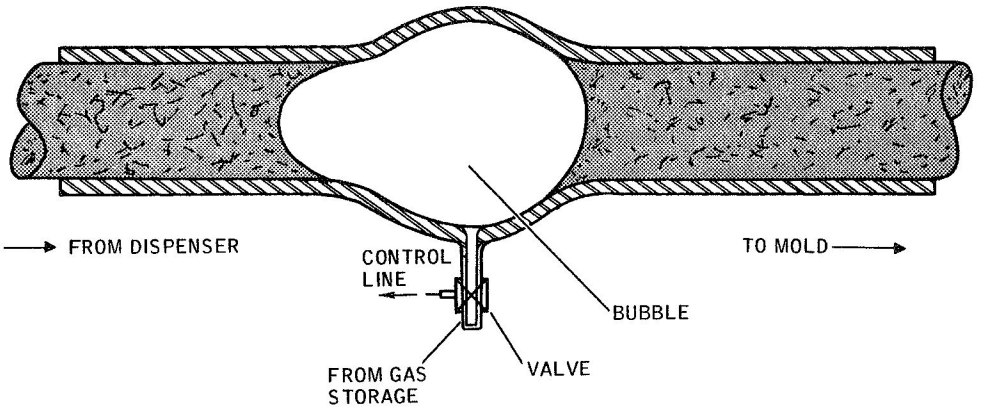

Figure 11. Gas bubble cutoff.

CASTING SHAPES AND RELATED TOOLING

For the initial experiments, casting shapes have been selected to provide maximum data and experience with a minimum of tooling and weight.

For general casting applications, three basic configurations are proposed for testing materials, shape effects, and casting procedures: A full cylinder, for basic casting tests and materials data; a tubular shape, representing more complex "thin"-wall castings; and a flat plate, for investigation of material flow and reinforcement uniformity, as well as foamed composites.

Two additional shapes are designed for research experiments on advanced zero-g casting techniques with composites as well as monolithic material: a disk with a raised section for investigation of adhesion casting and the effect of shape discontinuities upon spreading rate and thickness uniformity; and a sphere for surface tension casting, as well as for the investigation of solidification phenomena without mold wall interference. For the sake of tooling simplicity, the sphere remains — at least in the initial experiment — attached to the dispensing nozzle, which covers less than 2% of its surface.

The dimensions and the maximum casting weights for the discussed five shapes are identified on Table 5; the molds and related tooling are illustrated in Figure 12.

For heating, two interchangeable assembles are required: a box-shaped unit for the closed molds (A, B, C of Figure 12) and a spherical unit for surface tension and adhesion casting (D, E). Both units consist of two identical halves, which swing away for radiation cooling. The spherical unit, in closed position, provides complete sealing against environment to permit pressurization and melt evaporation control.

Table 5. Experimental casting shapes & weights.

MOLD TYPE	CASTING SHAPE	CASTING DIMENSION (IN.)	CASTING WEIGHT (LB.)*	
			AL-BASE	Ni-BASE
A	CYLINDRICAL	2 DIA. X 10	3.8	10.2
B	TUBULAR	2.5 I.D. X 1.75 O.D. X 10	3.0	8.1
C	FLAT PLATE	4 X 10 X 3/4	3.6	9.6
D	SPHERE	4 OD, MAX.	3.8	10.4
E	MODIFIED DISK	DISK DIA. 7	2.4	6.4

* MAXIMUM; VARIES WITH REINFORCEMENT CONTENT.

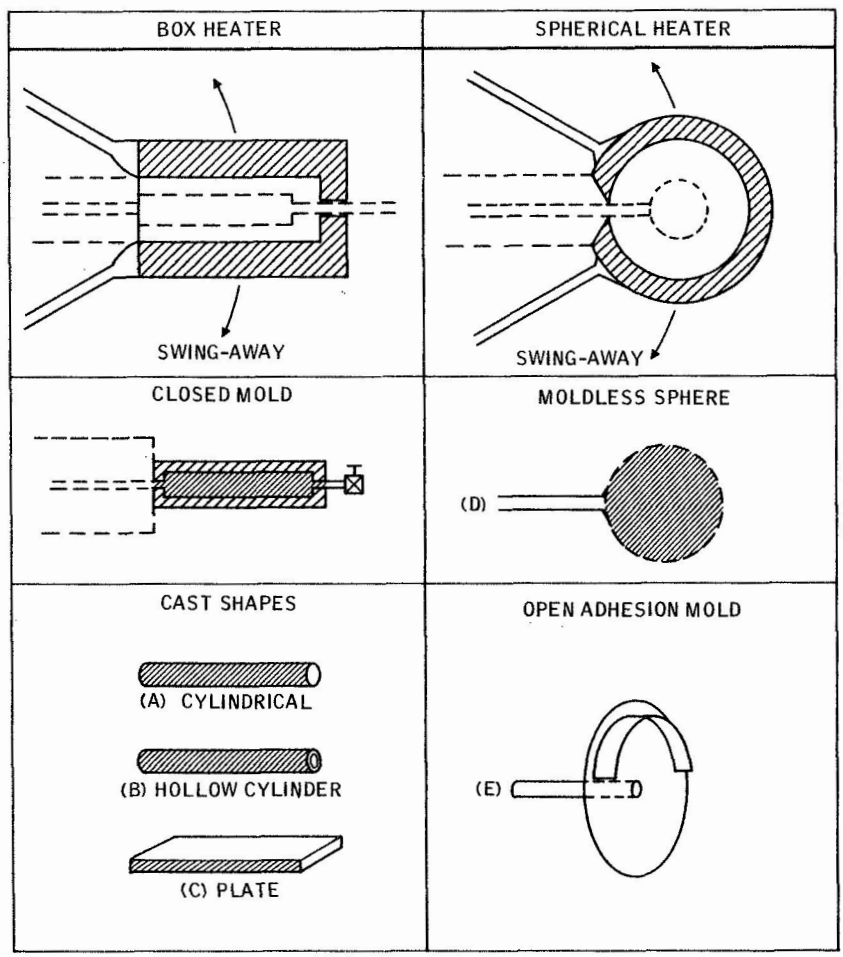

Figure 12. Molds and casting shapes.

EXPERIMENT PERFORMANCE

The major processing and operational steps of each individual casting experiment are identified in Figure 13. Each step is activated and observed by an astronaut, while all processing details are preset and controlled automatically. Experiment preparation and retrieval of the casting after experiment completion requires two men. Approximate power requirements for individual experiments are:

Al-Base 2 kw for 2 hours + 0.5 kw for 1 hour

Ni-Base 2 kw for 3 hours + 1 kw for 1 hour

EXPERIMENT PROGRAM

The concept of composite casting is aimed at an early use as a space manufacturing process. This calls for an early availability of conclusive engineering data. As pointed out earlier, this can only be achieved with a versatile experiment facility similar to the one proposed earlier. This facility, supported by the extensive capabilities of the advanced orbital workshop, permits performance of series of individual casting experiments in which a well-planned variation of materials, processing details, and product shapes generates a maximum amount of reliable engineering data.

An example for such a program is presented in Table 6, which integrates the material types, process modifications, and casting shapes defined earlier in this discussion. It consists of 16 experiment series arranged in four groups:

1. Aluminum-whisker composites.
2. Aluminum-whisker-particle composites.
3. Nickel-whisker composites.
4. Nickel-whisker-particle composites.

Each series represents one material composition to facilitate the potential use of premixed ingots as raw material. The seven individual experiments of each series provide for the most effective variation of processes and casting shapes.

The rather systematic program can be arranged timewise in various more or less ambitious schedules. One could, for instance, emphasize in a first phase the evaluation of materials, reducing the variation in processes and product shapes. If, on the other hand, each material composition is supplied in form of

Table 6. Experiment program - definition of individual experiments.

MATERIALS				CASTINGS - SHAPES*					EXP. (NET)
MATRIX	WHISKERS		PARTICLES	AS CAST	ORIENTATION CONTROL	VARIABLE DISTRIBUTION	FOAM 20%	FOAM 50%	
Al	Al_2O_3	5%	—	ADE		BC		AC	7
	Al_2O_3	15%	—	ACD	BC		AC		7
	Al_2O_3	25%	—	ABC	BC		AC		7
	Al_2O_3+Al N	25%	—	ABC	BC		AC		7
Al	—		0.01%	ADE		BC		CD	7
	—		0.1 %	ADE		BC		CD	7
	Al_2O_3	5%	0.1 %	ACE		BC		AC	7
	Al_2O_3	25%	0.01%	ABC	BC		AC		7
	Al_2O_3+Al N	25%	0.01%	ABC	BC		AC		7
Ni	SiC	5%	—	ADE		BC		AC	7
	SiC	15%	—	ACD	BC		AC		7
	SiC	25%	—	ABC	BC		AC		7
Ni	—		0.01%	ADE		BC		CD	7
	—		0.1 %	ADE		BC		CD	7
	SiC	5%	0.1 %	ACE	BC		AC		7
	SiC	25%	0.01%	ABC	BC		AC		7
TOTAL EXPERIMENTS				48	18	14	18	14	112

*CASTING SHAPES, DIMENSIONS & WEIGHTS ARE IDENTIFIED IN FIGURE 12 & TABLE 5

one ingot, the completion of horizontal series in Table 6 is almost mandatory; it is even feasible to carry out each series in one single heat, so that it could be considered as one experiment. This approach would further generate early experience in process engineering and tooling as a basis for potential program revisions.

To convey an overall picture of the magnitude of the program, the total number of individual experiments and the related net material weights to be shipped to and from orbit are summarized in Table 7, arranged in three phases with increasing complexity and processing temperature. While the total program may appear ambitious in terms of experiment number, it turns out to be rather modest in terms of material weight.

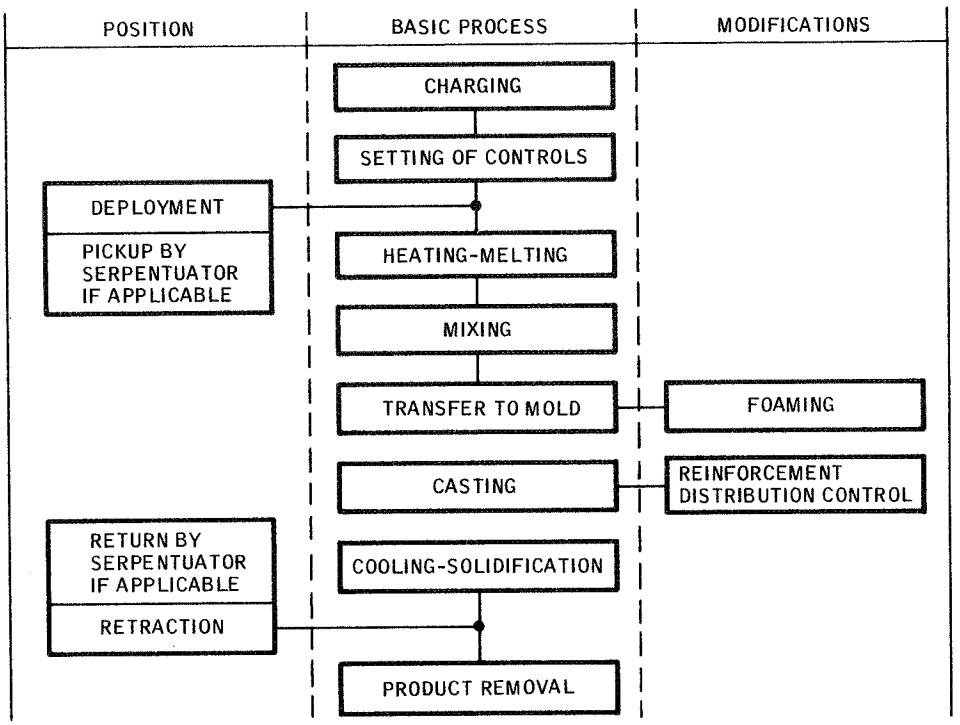

Figure 13. Sequence of major processing steps.

Table 7. Experiment program summary.

EXPT. PHASE	OBJECTIVE	NUMBER OF			MATERIAL WEIGHT (LB.)	
		INGOTS	CHECK EXP.	CASTG. EXP.	DEPLOY.	RETURN
I	HIGH-STRENGTH ALUMINUM-WHISKER COMPOSITES	4	6	28	250	110
II	HIGH-STRENGTH Al-WHISKER COMPOSITES WITH MICRO-STRUCTURE CONTROL	5	5	35	310	135
III	HIGH-STRENGTH & CREEP RESISTANT NICKEL-WHISKER COMPOSITES; MICROSTRUC-TURE CONTROL	7	6	49	1,150	450

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